

Current-induced magnetization dynamics at the edge of a two-dimensional electron system with strong spin-orbit coupling

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We experimentally investigate electron transport through the interface between a permalloy ferromagnet and the edge of a two-dimensional electron system with strong Rashba-type spin-orbit coupling. We observe strongly non-linear transport around zero bias at millikelvin temperatures. The observed nonlinearity is fully suppressed above some critical values of temperature, magnetic field, and current through the interface. We interpret this behavior as the result of spin accumulation at the interface and its current-induced absorption as a magnetization torque.

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I. INTRODUCTION

Recently, there is a strong interest in semiconductor hybrid structures, which consist of a metal and a low-dimensional semiconductor structure with strong spin-orbit (SO) coupling. The general interest is devoted to the modification of transport in the low-dimensional structure caused by the proximity with a metal, which is characterized by a macroscopic order parameter. In the case of a superconducting metal, the interest is mostly stimulated by the search for Majorana fermions.¹

As a superconductor, also a ferromagnet (F) is characterized by a macroscopic order parameter. In the case of a ferromagnet, there is the possibility of injection and detection of spin-polarized electrons. This is important, e.g., for investigations of the spin-Hall effect, which manifests itself as finite spin accumulation at the sample edges, generated by an electric field in a low-dimensional system with strong SO coupling². The existence of the spin-Hall effect^{3,4} was firstly confirmed in transport investigations of thin metallic films^{5,6} and much later in optical experiments^{7,8} in semiconductors.

On the other hand, a more general problem can be formulated: the mutual influence of two systems at the interface between them. In the case of a superconducting metal close to a two-dimensional electron gas (2DEG), Andreev reflection is suppressed because the strong SO coupling affects pairing near the interface^{9,10}. In the case of a ferromagnet, spin-dependent transport through the F-2DEG interface defines the current-induced magnetization dynamics in a ferromagnetic contact¹¹, e.g. magnetization torque¹². The latter effect was mostly investigated in multilayer systems^{13–15}, which consist of a set of normal and ferromagnetic layers. A 2DEG realized in a semiconductor quantum well, differs significantly from a thin metallic film. In particular, a 2DEG edge is well-known to exhibit a very specific one-dimensional behavior both in quantizing¹⁶ and in zero¹⁷ magnetic fields. Thus, it is quite reasonable to study spin transport in

a F-2DEG planar device located at the edge of a 2DEG with strong Rashba-type SO coupling.

Here, we experimentally investigate electron transport through the interface between a permalloy ferromagnet and the edge of a two-dimensional electron system with strong Rashba-type spin-orbit coupling. We observe strongly non-linear transport around zero bias at millikelvin temperatures. The observed nonlinearity is fully suppressed above some critical values of temperature, magnetic field, and current through the interface. We interpret this behavior as a result of spin accumulation at the interface and its current-induced absorption as a magnetization torque.

II. SAMPLES AND TECHNIQUE

Our samples are grown by solid source molecular beam epitaxy on semi-insulating GaAs (100) substrates. The active layer is composed of a 20-nm thick $In_{0.75}Ga_{0.25}As$ quantum well sandwiched between a lower 50-nm thick and an upper 120-nm thick $In_{0.75}Al_{0.25}As$ barrier. Details on the growth parameters can be found elsewhere^{18,19}. A two dimensional electron gas, confined in a narrow asymmetric $In_{0.75}Ga_{0.25}As$ quantum well, is characterized by strong Rashba-type SO coupling^{20,21}. For our samples, the 2DEG mobility at 4K is about $5 \cdot 10^5 \text{ cm}^2/\text{Vs}$ and the carrier density is $4.1 \cdot 10^{11} \text{ cm}^{-2}$, as obtained from standard magnetoresistance measurements.

A sample sketch is presented in Fig. 1. A 200 nm high mesa is formed by wet chemical etching. In our $In_{0.75}Ga_{0.25}As$ structure, a high quality contact to a 2DEG edge can be realized by evaporation of a metal over the mesa edge, without annealing procedure^{9,21}. We fabricate two Ohmic contacts to the 2DEG by thermal evaporation of 100 nm Au (with few nm Ni to improve adhesion). These Ohmic contacts are characterized by a constant ($\approx 1k\Omega$) resistance. In addition, we use rf sput-

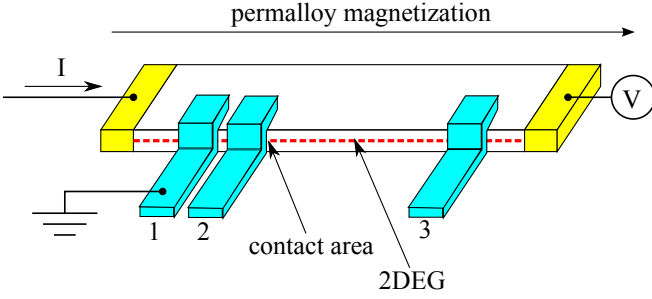


FIG. 1. (Color online) Sketch of the sample with electrical connections (not in scale). The $100\ \mu\text{m}$ wide mesa has two Au Ohmic contacts (yellow). Three ferromagnetic $\text{Fe}_{20}\text{Ni}_{80}$ permalloy stripes (blue, denoted by numbers) are placed to overlap the mesa step. In every overlap region, a planar F-2DEG junction is formed between the ferromagnetic film and the 2DEG edge (denoted by a dashed line). The width of each junction is equal to $20\ \mu\text{m}$. The junctions 1 and 2 are separated by $2\ \mu\text{m}$ distance, while junction 3 is shifted by $400\ \mu\text{m}$ along the mesa edge. We study electron transport across one particular F-2DEG junction in a three-point configuration: the corresponding ferromagnetic electrode is grounded (no. 1 in the figure), others are disconnected; a current is applied between it and one of the Au Ohmic contacts; the other Au contact traces the 2DEG potential.

tering to deposit 50 nm thick ferromagnetic $\text{Fe}_{20}\text{Ni}_{80}$ permalloy stripes to overlap the mesa edge. The initial magnetization of the permalloy is oriented along the mesa edge, see Fig. 1. The stripes are formed by lift-off technique, and the surface is mildly cleaned by Ar plasma before sputtering. To avoid any 2DEG degradation, the sample is not heated during the sputtering process.

A planar F-2DEG junction is formed between the ferromagnetic electrode and the 2DEG at the mesa edge. We study electron transport across one particular F-2DEG junction in a three-point configuration: a current is applied between one of the Au Ohmic contacts and a ferromagnetic electrode which is grounded (contact 1 in Fig. 1) while the other Au contact measures the 2DEG potential. To obtain $dV/dI(V)$ characteristics, we sweep the dc current through the interface from $-5\ \mu\text{A}$ to $+5\ \mu\text{A}$. This dc current is modulated by a low (0.85 nA) ac (110 Hz) component. We measure both the dc (V) and ac ($\sim dV/dI$) components of the 2DEG potential by using a dc voltmeter and a lock-in amplifier, respectively. We have checked, that the lock-in signal is independent of the modulation frequency in the range 50 Hz – 300 Hz. This range is defined by applied ac filters. Because of the relatively low in-plane 2DEG resistance (about $100\ \Omega$ at present 2DEG concentration and mobility), and the low resistance of the metallic permalloy electrode, the measured $dV/dI(V)$ curves reflect the behavior of the F-2DEG interface. To extract features specific to the SO coupling, the measurements were performed at a temperature of 30 mK. Similar results were obtained from different samples in several cooling cycles.

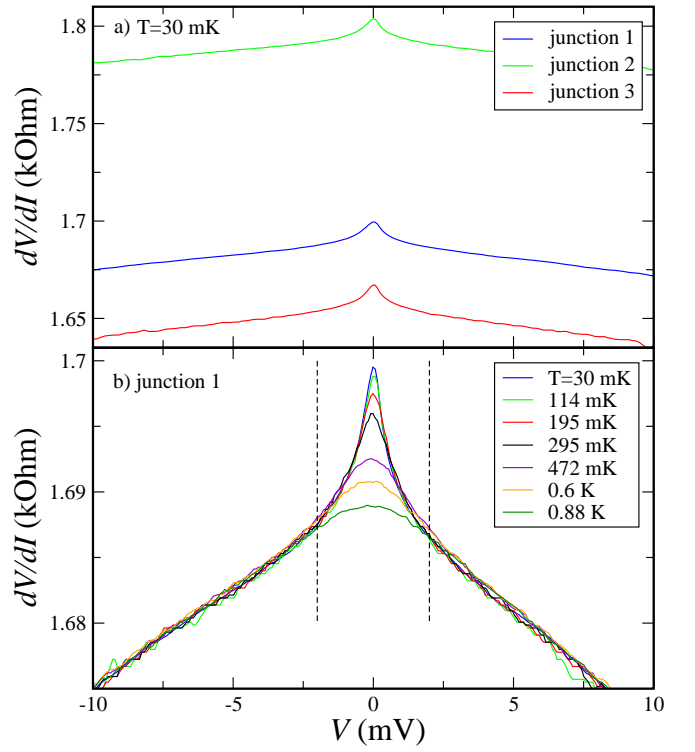


FIG. 2. (Color online) (a) Differential resistance dV/dI of a single F-2DEG junction as a function of the dc voltage drop V across the junction. The curves are denoted by the junction numbers, see Fig. 1. Each curve demonstrates a well developed non-linear behavior at low bias. The curves from three F-2DEG junctions only differ by a constant and bias-independent offset. (b) Evolution of the $dV/dI(V)$ curve with temperature. The non-linear region around zero bias exists only at low temperatures and disappears completely at 0.88 K. On the other hand, the linear branches of the $dV/dI(V)$ curves are invariant in this temperature range.

III. SINGLE F-2DEG JUNCTIONS

A. Results

Examples of $dV/dI(V)$ characteristics are presented in Fig. 2(a) for three different F-2DEG junctions, depicted in Fig. 1. All three experimental curves in Fig. 2(a) look quite similar: they only differ by a constant and bias-independent offset. The offset absolute value does not correlate with the junction position along the mesa edge: the measured resistance is maximum for the junction 2, which is not the closest one to the current or voltage Ohmic contacts. This is another experimental verification that the measured resistance is a characteristics of one particular F-2DEG interface, see also Section IV.

Each curve in Fig. 2(a) demonstrates strongly non-linear behavior, which is shown in detail in Fig. 2(b) for the junction 1. The curve is slightly asymmetric with respect to voltage and is characterized by a strictly linear dependence of $dV/dI(V)$, except in the narrow re-

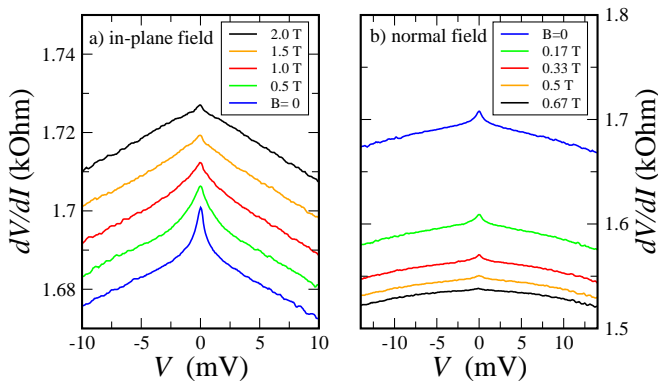


FIG. 3. (Color online) Suppression of the zero-bias nonlinearity by (a) in-plane or (b) perpendicular magnetic field at $T = 30$ mK. The full suppression occurs at $B = 2$ T for the in-plane oriented magnetic field while it occurs at much lower field ($B = 0.67$ T) for the perpendicular field orientation. The linear branches of the $dV/dI(V)$ curves demonstrate positive (a) or negative (b) bias-independent magnetoresistance.

gion around zero bias. A temperature increase suppresses the zero-bias non-linearity. The non-linearity disappears completely at 0.88 K. In contrast, the linear branches of the $dV/dI(V)$ curve are invariant in this temperature range.

Similarly to temperature, the zero-bias nonlinearity in dV/dI can be suppressed by a magnetic field, as shown in Fig. 3. The full suppression occurs at quite high $B = 2$ T for an in-plane oriented field while it occurs at much lower field ($B = 0.67$ T) for the perpendicular field orientation. The linear branches of the $dV/dI(V)$ curves demonstrate bias-independent magnetoresistance, which is positive (a) or negative (b), depending on the magnetic field orientation.

B. Discussion

Let us start the discussion with the $dV/dI(V)$ curves with suppressed zero-bias nonlinearity, i.e. from Fig. 2(b) at higher temperature (0.88 K) or from Fig. 3(a) above 1.5 T. The linear dependence of $dV/dI(V)$, outside the zero bias region as well as the clear asymmetry of the curve, differs significantly from usual Ohmic behavior with constant $dV/dI(V)$. This behaviour indicates the presence of a (narrow) potential barrier at the interface between the ferromagnet and the 2DEG, e.g. due to depletion at the 2DEG edge¹⁷. From the constant slope of the linear branches in Figs. 2 and 3 we can conclude that in our experiment the barrier is roughly independent of temperature and magnetic field. Apart from the barrier, the junction resistance is affected by single-particle scattering due to 2DEG disorder in the vicinity of the interface. The disorder is responsible for different offset values observed for different junctions as shown in Fig. 2(a). Both barrier and disorder define a single-

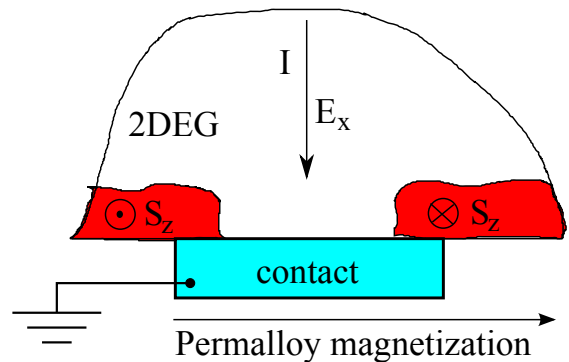


FIG. 4. (Color online) Top-view of the 2DEG region near the ferromagnetic contact (see Ref. 22 for details) with zero magnetic field for the case of a strong Rashba SO coupling. The electric current I is flowing through the 2DEG to the F-2DEG interface. The corresponding electric field E_x creates a non-zero, out-of-plane spin polarization S_z around the junction corners (red regions, not in scale), because of a spin-Hall effect. The permalloy film magnetization is oriented within the 2DEG plane.

particle transmission of the interface which we can estimate to be $T \approx 0.1$ from the junction resistance and width. This T value is slightly different (below 10%) for different junctions, which is in agreement with the disorder variation observed in Ref. 19 for similar samples.

However, both disorder and potential barrier are junction-specific values, so they cannot be responsible for the quite universal zero-bias nonlinearity in dV/dI at low temperature. On the other hand, characteristic values of the non-linearity suppression ($T \approx 1$ K and $B \approx 1.5$ -2 T in-plane field) are well known for the 2DEG in our $In_{0.75}Ga_{0.25}As$ quantum well: the spin-orbit splitting Δ_{SO} is about 0.1 meV in zero magnetic field^{9,20}, while Zeeman splitting exceeds^{9,20} Δ_{SO} for in-plane $B > 1.5$ T. For this reason and because the observed non-linearity is quite universal for different junctions, it seems to be reasonable to connect the observed nonlinearity with spin effects due to the Rashba SO coupling.

The spin effects are expected to be quite sophisticated in the vicinity of the interface²². At zero magnetic field, the electric field E_x , which originates from flowing current, is expected to cause a non-zero spin current j_y^z in a clean, infinite and homogeneous 2DEG²³, which is well known as a spin-Hall effect. However, the spin current is not measurable directly, so its physical meaning is obscure²². A more meaningful quantity is spin polarization (spin accumulation) rather than a spin current. Calculations that included scattering²⁴ resulted in $j_y^z = 0$, and $j_y^z = 0$ has been also proven directly even in absence of scattering²⁵. Despite this fact, spin polarization S_z near the edges even in absence of spin current has been found in a number of theoretical papers, see, e.g., Refs. 26 and 27. Thus, out-of-plane spin polarization S_z is accumulated around the corners²², see Fig. 4. Since the permalloy film has in-plane magnetization, transport of

out-of-plane polarized electrons to the contact is difficult because the necessary absorption of a polarization component perpendicular to the permalloy magnetization. The junction width is effectively diminished, which gives rise to the increased differential resistance dV/dI around zero bias as shown in Fig. 2.

When we increase the current through the interface, this out-of-plane spin polarization can be transferred to the permalloy magnetization as a magnetization torque¹². This restores the contact effective width, so the differential resistance is diminished exactly to the same values as obtained by a temperature increase as shown in Fig. 2(b). The current-induced polarization absorption is characterized¹² by some critical current value, which can be estimated from Fig. 2(b) as $\approx 1\mu\text{A}$. This relatively low¹¹ value originates from the specific geometry: the planar junction is formed by a thin permalloy film at vertical mesa edge. If we consider the finite 2DEG thickness, we obtain quite reasonable¹² critical current density of $10^4 - 10^5 \text{ A/cm}^2$.

The above picture is essentially based on the presence of a strong Rashba-type spin-orbit coupling in the 2DEG. If the temperature exceeds the value of the spin-orbit splitting $\Delta_{SO} \approx 0.1 \text{ meV}$, all the effects of the spin polarization disappear in the 2DEG, and the interface resistance is diminished, as we do observe in Fig. 2(b) at $T \approx 1 \text{ K}$. The nonlinearity observed in Fig. 2 is indeed induced by the current, because the nonlinearity bias range in Fig. 2(b) (about 4 mV) exceeds significantly the characteristic suppression temperature $T \approx 1 \text{ K}$. An in-plane magnetic field has a similar effect: when the Zeeman splitting exceeds Δ_{SO} at $B \approx 1.5 \text{ T}$, the spin-Hall effect disappears, and the interface resistance is diminished, as can be seen in Fig. 3(a). A positive, bias-independent magnetoresistance of the linear branches of the $dV/dI(V)$ curves reflects the spin-polarization of the 2DEG²⁸ and is not sensitive to spin-orbit effects.

The primary effect of a perpendicular magnetic field is different. It easily aligns already at lower magnetic field values ($B \approx 0.67 \text{ T}$) the magnetization of the soft permalloy ferromagnet to the field direction, i.e. in the S_z direction in this case. The transport through the F-2DEG interface does not require the perpendicular magnetization component absorption. Thus, the junction resistance is reduced, as we see in Fig. 3(b). Negative magnetoresistance of the linear branches of $dV/dI(V)$ curves is defined by the 2DEG orbital effects in a perpendicular field.

IV. DOUBLE F-2DEG-F JUNCTIONS

The above arguments are supported by the magnetic field behavior of F-2DEG-F junctions. We measured the bias-dependent differential resistance of F-2DEG-F junctions in a two-point configuration, by grounding one ferromagnetic stripe in Fig. 1 and using another to apply a current and to measure a voltage drop simultaneously.

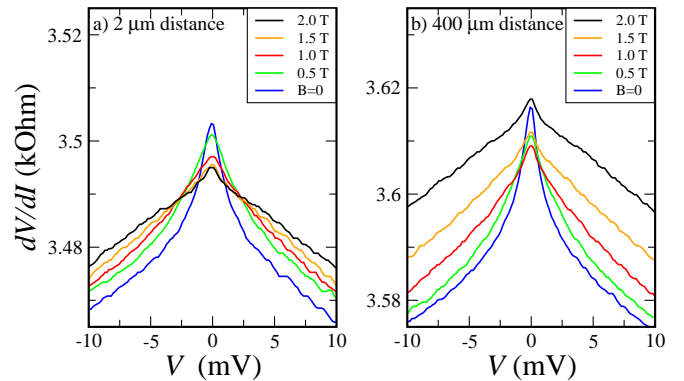


FIG. 5. (Color online) Two-point differential resistance dV/dI between two ferromagnetic leads (F-2DEG-F junction). (a) For the shorter distance between the leads ($2 \mu\text{m}$), the $dV/dI(V)$ curve is exactly the sum of the $dV/dI(V)$ characteristics of two F-2DEG junctions (at zero field). (b) For larger distance between the leads ($400 \mu\text{m}$), the $dV/dI(V)$ curve contains a noticeable (about 100Ω) 2DEG resistance between the leads, compare the corresponding curves in Fig. 2(a). In-plane magnetic field suppresses the zero-bias nonlinearity equally in both cases, demonstrating that it is determined by spin effects at the interface.

First we will show that the non-linearity is determined by the interface, see Fig 5. The contacts 1 and 2 are separated by a distance of $2 \mu\text{m}$, which is below the $10 \mu\text{m}$ mean free path in the 2DEG. It is thus not surprising that the $dV/dI(V)$ curve in Fig 5(a) at $B = 0$ is exactly the sum of the two corresponding $dV/dI(V)$ characteristics from Fig. 2(a). The positive magnetoresistance is very weak in this case, because the ballistic transport is less sensitive to the 2DEG between the two ferromagnetic contacts. For the long ($400 \mu\text{m}$) F-2DEG-F junction, see Fig 5(b), the $dV/dI(V)$ curve contains a noticeable (about 100Ω) 2DEG resistance even in zero magnetic field (compare the corresponding values in Figs. 2(a) and 5(b)). In this case the positive magnetoresistance is practically restored.

However, in both cases, the zero-bias nonlinearity suppression by the in-plane magnetic field is exactly the same as in the case of a single junction. We can thus conclude that the non-linearity is determined by the interface.

Next, ballistic, spin-dependent transport in the vicinity (about $2 \mu\text{m}$) of a junction is demonstrated in Fig. 6. For larger distance ($400 \mu\text{m}$) between the leads (red line), the $dV/dI(B)$ curve is a sum of xx and xy magnetoresistance components, as expected for a quantum Hall two-point measurements. However, the $dV/dI(B)$ demonstrates a clear Hall (xy) behavior for the short ($2 \mu\text{m}$) distance between the leads (blue line) already at very low magnetic fields, see inset to Fig. 6.

In a quantizing magnetic field, the bulk spectrum of a 2DEG is a Landau ladder with additional Zeeman (spin) sub-splitting. Current-carrying edge states at the sample edge¹⁶ are therefore characterized by the out-of-plane spin projection. A perpendicular magnetic field easily

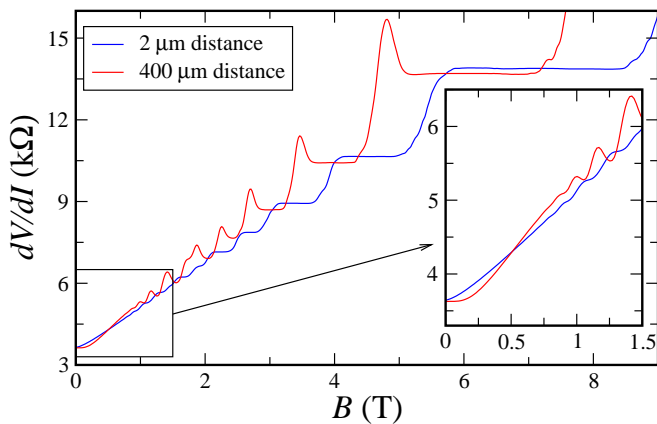


FIG. 6. (Color online) Two-point magnetoresistance dV/dI between two ferromagnetic leads (F-2DEG-F) at zero bias in perpendicular field. For large (500 μm) distance between the leads (red line), the $dV/dI(B)$ curve is the sum of the xx and xy magnetoresistance components, as expected for a two-point measurements. However, for the short (2 μm) distance between the leads (blue line), the $dV/dI(B)$ demonstrates a clear quantum Hall behavior. The inset shows that this behavior occurs even at very low magnetic fields.

aligns the magnetization of the soft permalloy ferromagnet to the field direction. In the case of two-point measurements, (out-of-plane) spin-polarized electrons are injected into the edge state with the same spin projection. For the short F-2DEG-F junction, electrons travel along the edge states and are absorbed in the other ferromag-

netic electrode with the same spin projection. In the case of a long junction, charge redistribution takes place between the edge states, which is accompanied by a spin-flip. Thus, only part of the electrons can be absorbed at the end. Therefore, for the short F-2DEG-F junction, we have a perfect quantum Hall behavior even for the two-point measurements, while in the larger junction we have the usual sum of the xx and xy resistance components. This behavior demonstrates ballistic, spin-dependent transport in the close vicinity of the F-2DEG interface.

V. CONCLUSION

We experimentally investigate electron transport through the interface between a permalloy ferromagnet and the edge of a two-dimensional electron system with strong Rashba-type spin-orbit coupling. We observe strongly non-linear transport around zero bias at millikelvin temperatures. The observed nonlinearity is fully suppressed above some critical values of temperature, magnetic field, and current through the interface. We interpret this behavior as a result of spin accumulation at the interface and its current-induced absorption as a magnetization torque.

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